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# $^{40}Ar/^{39}Ar$ and $^{14}C$ geochronology of the Albano maar deposits: Implications for defining the age and eruptive style of the most recent explosive activity at Colli Albani Volcanic District, Central Italy

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A B S T R A C T

New $^{40}Ar/^{39}Ar$ and $^{14}C$ ages have been found for the Albano multiple maar pyroclastic units and underlying paleosols to document the most recent explosive activity in the Colli Albani Volcanic District (CAVD) near Rome, Italy, consisting of seven eruptions (Albano 1 = oldest). Both dating methodologies have been applied on several proximal units and on four mid-distal fall/surge deposits, the latter correlated, according to two current different views, to either the Albano or the Campi di Annibale hydromagmatic center. The $^{40}Ar/^{39}Ar$ ages on leucite phenocrysts from the mid-distal units yielded ages of ca. 72 ka, 73 ka, 41 ka and 36 ka BP, which are indistinguishable from the previously determined $^{40}Ar/^{39}Ar$ ages of the proximal Albano units 1, 2, 5 and 7, thus confirming their stratigraphic correspondence.

Twenty-one $^{14}C$ ages of the paleosols beneath Albano units 3, 5, 6 and 7 were found for samples collected from 13 proximal and distal sections, some of which were the same sections sampled for $^{40}Ar/^{39}Ar$ measurements. The $^{14}C$ ages were found to be stratigraphically inconsistent and highly scattered, and were systematically younger than the $^{40}Ar/^{39}Ar$ ages, ranging from 35 ka to 3 ka. Considering the significant consistence of the $^{40}Ar/^{39}Ar$ chronological framework, we interpret the scattered and contradictory $^{14}C$ ages to be the result of a variable contamination of the paleosols by younger organic carbon deriving from the superficial soil horizons.

These results suggest that multiple isotopic systems anchored to a robust stratigraphic framework may need to be employed to determine accurately the geochronology of the CAVD as well as other volcanic districts.



## 1. Introduction and general background

Hazard evaluation in active volcanic areas requires documentation on the style, magnitude, source area and frequency of the eruptions and other dangerous volcanic phenomena (e.g. gas emission, sin- or post-eruptive lahars, etc.). However, based on the strict definition proposed in the Smithsonian Institution's catalogue of active volcanoes, only volcanoes that have erupted in the last 10,000 years should be considered active. Alternatively, it is considered that a volcano is dormant when the time elapsed since its last eruption does not exceed the average recurrence period of its past activity.

Establishing the age of the most recent activity that occurred at the Colli Albani Volcanic District, central Italy, documented at the Albano multiple maar (De Rita et al., 1995a,b; Funiciello et al., 2002, 2003; Freda et al., 2006; De Benedetti et al., 2008), is therefore fundamental to evaluate the time elapsed since the last eruptive event as well as its activity status. This has a relevant implication on the assessment of the potential hazard for the city of Rome, whose southeastern suburb reaches close to the slopes of the Albano crater.

Though many radioisotopic age determinations were made near the end of the last Century for the Colli Albani Volcanic District (for a review see Voltaggio and Barbieri, 1995), these were not the result of systematic study. Rather, they were a collection of data from many different sources, which often yielded contrasting results depending on the applied dating methodology. Therefore, uncertainty persisted regarding the age of the latest volcanic activity (e.g. De Rita et al., 1995a). Karner et al. (2001) carried out a $^{40}Ar/^{39}Ar$ age study of the Monti Sabatini and Colli Albani volcanic districts in order to provide sound radioisotopic ages for the eruptive history and to provide the required groundwork to assess the volcanic hazard for Rome (Fig. 1). Later on, Marra et al. (2003) expanded the geochronological picture for the Colli Albani, showing inconsistency between $^{40}Ar/^{39}Ar$ ages

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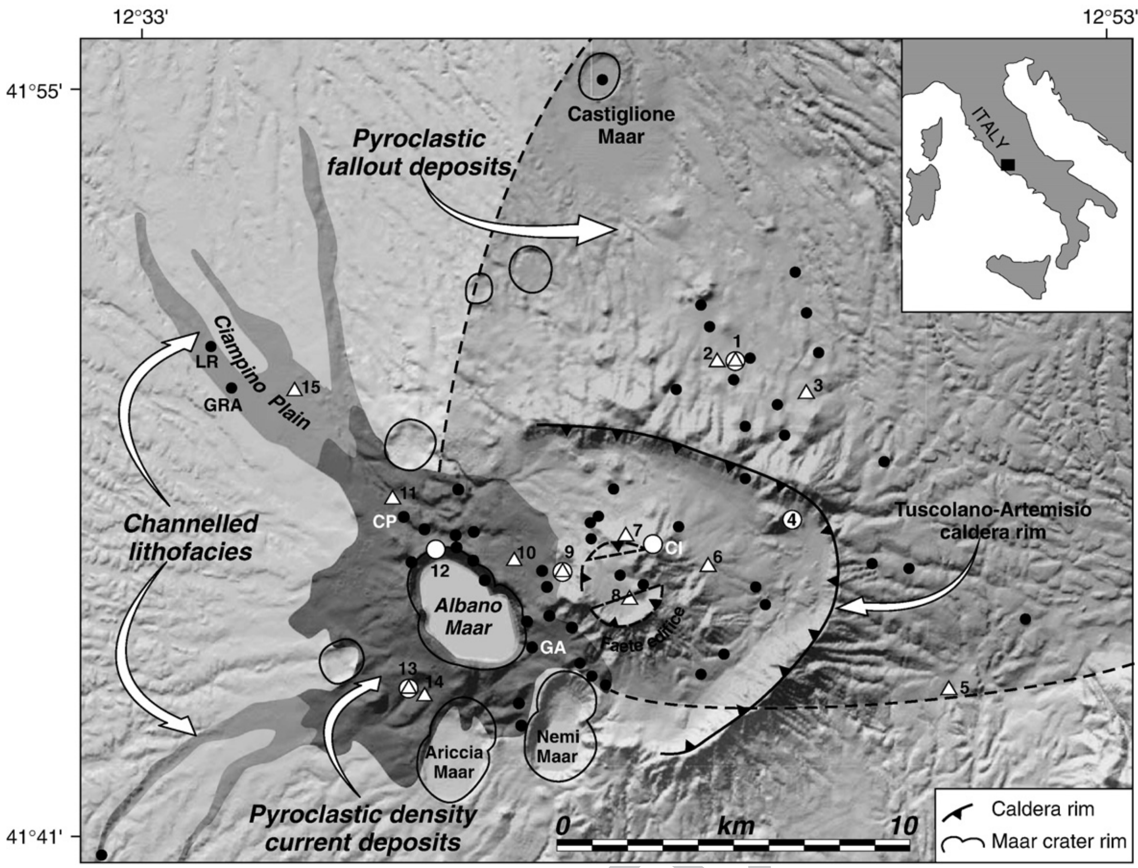


**Fig. 1.** Reference map of the investigated sections of the Albano maar products distributed in the three main depositional domains of the (*i*) proximal pyroclastic density current, (*ii*) distal fallout (Albano DUn of Giaccio et al., 2007) and (*iii*) distal channeled deposits. White circles: sampled sections for $^{40}Ar/^{39}Ar$ dating; white triangles: sampled sections for $^{14}C$ age determinations; black dots: other investigated sections. Numbers refer to sections mentioned in the text.



and previously published U/Th measurements that provided very young ages (Voltaggio and Barbieri, 1995). These studies enabled Marra et al. (2004) to estimate an average recurrence interval of approximately 45 kyr for the overall activity at the Colli Albani Volcanic District. Ensuing studies were focused on the youngest volcanic deposit of Colli Albani Volcanic District, called "Peperino Albano pyroclastic flow" and erupted from the Albano multiple maar (De Rita et al., 1995a,b). Leucite from this unit yielded a $^{40}Ar/^{39}Ar$ age of $36 \pm 1$ ka (Freda et al., 2006; see also Marra and Karner, 2005 for a discussion), which is in good agreement with the previously $^{14}C$ age determinations performed on unburned wood fragments embedded in the Peperiono Albano deposits (Fornaseri et al., 1963; Fornaseri and Cortesi, 1989). Based on these recent studies, it becomes apparent that the time elapsed (36 kyr) since the last eruption is shorter than the estimated recurrence interval (45 kyr) for the Colli Albani Volcanic District. Therefore, the Colli Albani may conservatively be regarded as a dormant rather than extinct volcano (Marra and Karner, 2005). However, the existence of volcanic activity occurring at the Albano maar after this eruption, and extending to Holocene times, has been suggested (Funiciello et al., 2002, 2003; De Benedetti et al., 2008), based on the stratigraphic and geochronological evidences deriving from the study of relatively distal sections of chanelled Albano deposits (GRA and the LR sections in Fig. 1). In particular, these works interpreted the volcaniclastic deposits at the top of these successions to be derived from lahar emplacements, triggered by repeated and catastrophic overspill of the Albano crater's lake in Holocene times, that occurred, on the bases of two $^{14}C$ age determinations on paleosols, ca. 5.8 ka BP.

In the light of this volcanological and historical reconstruction of the Albano maar activity, and considering the relevance implication for the hazard assessment for the city of Rome, within the V3_1 Colli Albani research project founded by the Dipartimento di Protezione Civile (Italian Agency of Civil Protection) and the Istituto Nazionale di Geofisica e Vulcanologia (National Institute of Geophysics and Volcanology), a study was initiated to establish the age and eruptive style of the last eruptive activity or other volcanic manifestations in the Colli Albani Volcanic District. The study was based on an extensive field and laboratory investigations that allowed a refinement of the stratigraphic framework of the Albano maar suite and a substantial reassessment of the actual extension of the distribution area of these deposits (Giaccio et al., 2007). Based on this study and some additional field investigations, we selected the best type-sections of the Albano multiple maar pyroclastic units, occurring both in proximal and distal area, for $^{14}C$ age determinations on paleosols separating the primary deposits of the Albano activity and direct $^{40}Ar/^{39}Ar$ dating of potassium-bearing mineral separate from these volcanic deposits. The aim of the present work is thus twofold: (*i*) to verify, through $^{40}Ar/^{39}Ar$ measurements, the soundness of the lithostratigraphic- and geochemical-based correlation between the widespread distal deposits (Giaccio et al., 2007) and their proximal equivalents, previously dated by Freda et al. (2006); (*ii*) to assess the applicability and reliability of the $^{14}C$ dating on paleosols of the Colli Albani area. Results of this study are presented and discussed in this paper.

## 2. Geological setting and stratigraphic framework

The Albano crater (Fig. 1) is part of a system of multiple- or monogenic-maars produced by the most recent explosive activity of the late Quaternary Colli Albani Volcanic District (De Rita et al., 1995a; Villa et al., 1999; Karner et al., 2001; Funiciello et al., 2002; Marra et al., 2003; Soligo et al., 2003; Funiciello et al., 2003; Freda et al., 2006; Giaccio et al., 2007; De Benedetti et al., 2008). It is regarded as the youngest of the maar system that resulted from the coalescence of two (Freda et al., 2006) or more (De Rita et al., 1995b; Villa et al., 1999) craters.

On the basis of previous studies and some new filed investigations we have categorized the deposits of the Albano maar into three depositional settings, based on the distance from the vent, local geomorphologic conditions and other factors conditioning the sedimentary processes: (*i*) *proximal*, including the pyroclastic density current deposits dispersed from the crater to 6 km from the rim; (*ii*) *distal fallout*, which consists principally of fallout and lesser density current deposits dispersed in from 5 to 15 km to the east of the crater rim; and (*iii*) *distal channeled*, consisting of either primary or secondary channeled lithofacies dispersed along the valley to the northwest and southwest of the Albano crater (Fig. 1).

*Proximal deposits* — Within and around the crater rim, the Albano deposits form an 80-m thick pyroclastic sequence consisting of several eruptive units separated by paleosols (De Rita et al., 1995a,b; Freda et al., 2006; Giordano et al., 2006; De Benedetti et al., 2008). Recent studies (Freda et al., 2006; Giordano et al., 2006; Giaccio et al., 2007; De Benedetti et al., 2008) recognize a total of seven eruptive units, here labeled Albano 1 through Albano7 (A1–A7), corresponding to units a, b, b', c, d, e, f of Freda et al. (2006) (Table 1) and clustered in three eruptive cycles centered at 69 ± 1 (A1–A3), 39 ± 1 (A4–A5) and 36 ± 1 (A6–A7) ka (Freda et al., 2006; see also Section 3.2).

The refined stratigraphy provided in Giaccio et al. (2007) and new field evidence are here used to revaluate some of the correlations proposed in Freda et al. (2006) and to better constrain the eruptive cycles. In particular, we correlate the so called *Lapis Albanus* (known also as "Peperino di Marino" or "Peperino Albano") to unit A6. This is a strongly lithified channeled pyroclastic density current deposit, quarried by Romans since the IV Century B.C.), cropping out at the Petrare valley (site 11 in Fig. 1) and dated to 36 ± 1 ka (Karner et al., 2001; Freda et al., 2006). Similar lithofacies may, however, be associated to the youngest unit A7, cropping out northeast of the crater, as well as to the older A5, which, for this reason, were in their turn identified as "Peperino Albano" by Freda et al. (2006) and De Benedetti et al. (2008), respectively (Table 1).

Although these three different attributions of the "Peperino Albano" (Freda et al., 2006 [A7], De Benedetti et al., 2008 [A5] and this study [A6]) account for the difficulty in distinguishing the valley pond lithofacies of the deposits of the last three eruptions, our proposed correlation is based on the recognition of one of the most distinctive layers occurring within the Albano stratigraphic suite which act as good markers for reliable tephrostratigraphic correlations (Giaccio et al., 2007). In particular at Via Cave del Peperino (site CP in Fig. 1), the *Lapis Albanus* deposits overlay a well-sorted, clast-supported, lithic and crystal-rich layer, a marker fallout level distinctive of the unit Albano 5 (level A5c in Fig. 3 equivalent to the layer d-2 of Freda et al., 2006 and Giaccio et al., 2007).

On the other hand, we also exclude the correlation proposed by Freda et al. (2006) because the density current deposits of the unit A7 are predominantly dispersed in the south-eastern sector of the Albano maar, i.e. in opposite side of the typical dispersion area of the *Lapis Albanus* which fills the valleys to north-west of the crater. Furthermore, the former is characterized by the occurrence of abundant distinctive green scoria clasts (level A7a and A7b in Fig. 3) that are quite absent in the *Lapis Albanus* deposits.

As a consequence, among the three potential options, the A6 unit indeed appears as the most probable, if not the only possible, eruptive event responsible for the formation of the thick channeled deposits of the *Lapis Albanus*.

*Distal fallout deposits* — These consist of a succession of four pyroclastic units, labeled Albano DU1, DU2, DU3 and DU4, well documented in a wide area northeast of the maar from 5 km to 15 km eastward from the Albano crater rim (Fig. 1; Giaccio et al., 2007). In particular, Giaccio et al. (2007), on the basis of stratigraphic, textural, geochemical and isotopic signatures, correlated the four distal units to the proximal units of Freda et al. (2006) (which in that paper were labeled a, b, d and f), or units A1, A3, A5 and A7 in this paper (Table 1). New field investigations show a single occurrence of a further distal unit sandwiched between DU1(= A1) and DU2(= A3) within a lacustrine sequence cropping out at Monte Fiore (Fig. 2), which we, based on its stratigraphic position and general litological feature, correlate to the proximal unit A2.

Within paleo-topographic depressions of this area, distal units DU1 (= A1), DU2(= A3) and DU4(= A7) may be buried or partially eroded and substituted by a thick sequence of volcaniclastic deposits derived from these primary pyroclastic units (Giaccio et al., 2007).

The same succession was identified and mapped by Giordano et al. (2006), who correlated it to the Campi di Annibale hydromagmatic center, which is part of the "Monte delle Faete" phase of activity persisted from 308 to 250 ka (De Rita et al., 1988, 1995a; Marra et al., 2003).

**Table 1**
Schematic stratigraphies of the Albano maar products representative of the three main depositional domains and related correlation.

| Area | Albano Lake and surroundings | | Ciampino Plain | Eastern distal areas |
|---|---|---|---|---|
| **Prevailing lithofacies** | **Pyrocalstic density current deposits** | | **Primary end/or reworked channelled deposits** | **Primary fallout deposits** |
| **Stratigraphy** | This study | De Benedetti et al. (2008) | This study | Giaccio et al. (2007) |
| | Present, deep paleosol | | Pedogenized colluvial deposits | Present, deep paleosol |
| | ***Albano 7*** | ***Albalonga unit*** | ***GRA 5*** | ***Albano DU4*** |
| | Incipient paleosol | paleosol | Pedogenized colluvial deposits | Shallow paleosol |
| | ***Albano 6*** (*Lapis Albanus*) | ***Villa Doria unit*** | ***GRA 4*** | |
| | Shallow paleosol | paleosol | Pedogenized colluvial deposits | |
| | ***Albano 5*** | ***Peperino Albano*** (*Lapis Albanus*) | ***GRA 3*** | ***Albano DU3*** |
| | Moderately deep paleosol | paleosol | Pedogenized colluvial deposits | Deep Paleosol |
| | ***Albano 4*** | ***Cantone unit*** | | |
| | Deep Paleosol | paleosol | | |
| | ***Albano 3*** | ***Corona del Lago unit*** | ***GRA 2*** | ***Albano DU2*** |
| | Shallow paleosol | paleosol | Pedogenized colluvial deposits | Shallow paleosol |
| | ***Albano 2*** | ***Coste dei Laghi unit*** | | |
| | Shallow paleosol | paleosol | | |
| | ***Albano 1*** | ***Montagnaccio unit*** | ***GRA 1*** | ***Albano DU1*** |

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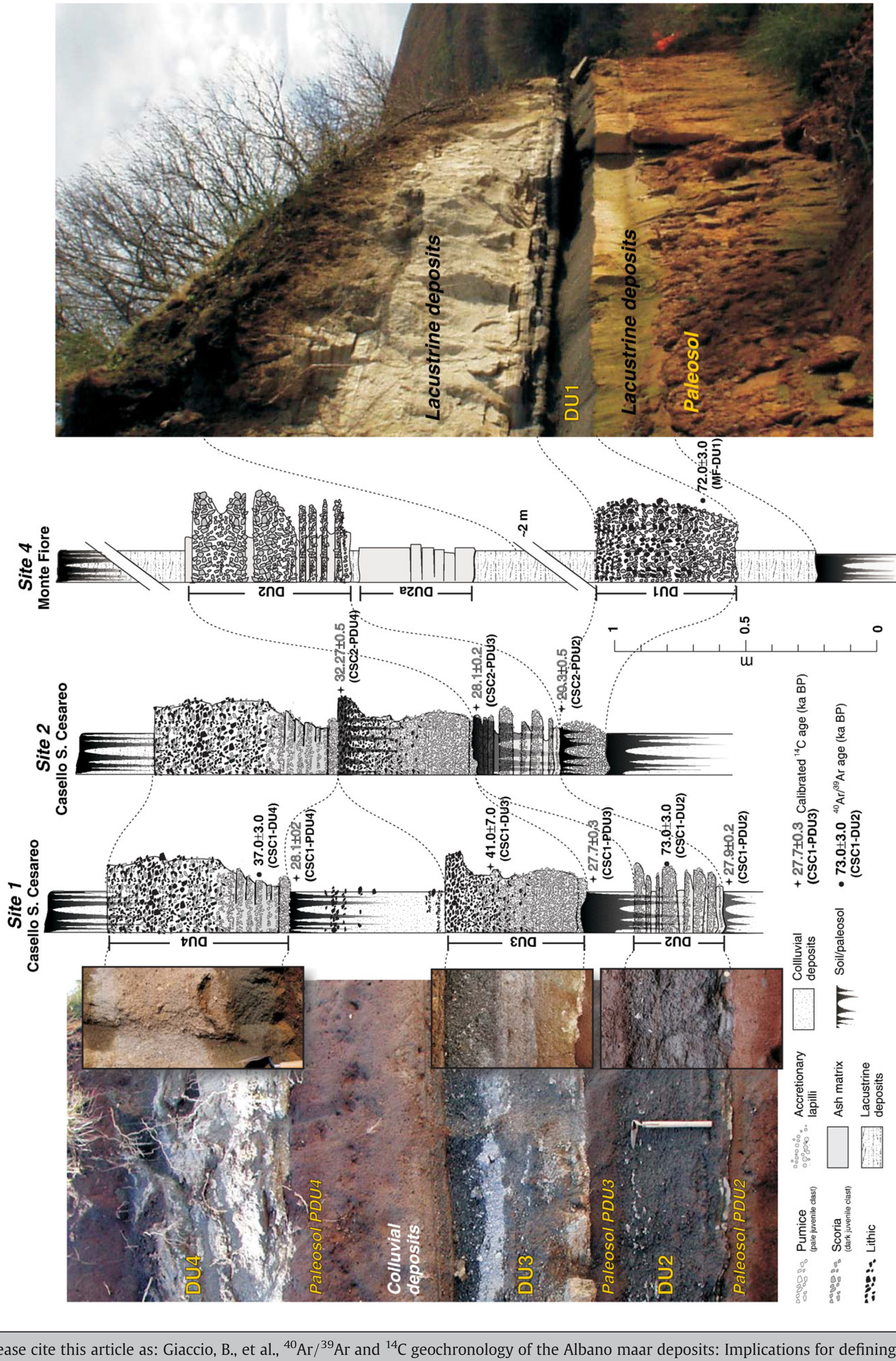


**Fig. 2.** Representative stratigraphic sections of the distal fallout deposits correlated to the Albano maar activity (Giaccio et al., 2007) sampled for both $^{40}Ar/^{39}Ar$ and $^{14}C$ age determinations. Site locations in Fig. 1.

More distally, equivalent ash layers have been recognised in a wide area of Central Italy (Giaccio et al., 2007). Establishing the origin and the age of these fallout deposits is thus relevant not only for the volcanology and geology of the Colli Albani area, but also for tephrochronological studies in the Central Apennine region.

*Distal channeled deposits* – These are pyroclastic successions comprising five either primary or reworked units recognized along the trench of the Grande Raccordo Anulare (GRA) roadway, in the area of the Ciampino Plain, approximately10 km northeast of the crater (Fig. 1) (Funiciello et al., 2002; Giordano et al., 2002; Funiciello et al., 2003; Freda et al., 2006). The lithological, geochronological and general stratigraphic features of the five units, here labeled GRA1 through GRA 5, allowed us to correlate them to the primary or reworked A1, A3, A5, A6 and A7, respectively (Table 1). This correlation is particularly robust for GRA1 because of its appreciable content of olivine, a mineral phase that is abundant only in A1 (Freda et al., 2006; Giaccio et al., 2007). Unit GRA2 is also straightforward to identify because it exhibits the peculiar stratigraphic and textural characteristics of A3 consisting in a rhythmic repetition of layers characterized by the presence of peculiar scoria clasts (see Freda et al., 2006 and Giaccio et al., 2007 for a detailed description). Although substantially reworked, the general lithological features of the GRA3, GRA4 and GRA5 units allow us to propose a tentative correlation with proximal unit A5, A6 and A7, respectively (Table 1). Previous studies (e.g. Funiciello et al., 2002, 2003) reported a substantially different interpretation and correlation.

For the geochronological purpose of the present paper, we adopt as a stratigraphic framework the refined proximal and distal stratigraphy provided in this section and by Giaccio et al. (2007), respectively, and summarized in Table 1.

## 3. Previous age determinations

### 3.1. Data selection

The current available knowledge on the Albano maar explosive history derives from both age measurements performed on proximal secessions, based on both $^{40}Ar/^{39}Ar$ (Villa et al., 1999; Marra et al., 2003; Freda et al., 2006) and $^{14}C$ (Fornaseri et al., 1963; Funiciello et al., 2002) methods, and varve-supported chronology of the Monticchio lacustrine record containing some tephra layers attributed to the Albano activity (Wulf et al., 2004). For the purpose of the present paper, however, we selected and discussed only the age measurements which were surely performed on Albano eruptive units, firmly defined in terms of their stratigraphic significance and position. For this reason we excluded the study by Villa et al. (1999) because it reports an age determined on a stratigraphically undefined Albano deposit, sampled at the base of a lacustrine core of the Albano lake. We also do not take into account the Monticchio tephrochronological record because the chemical composition of the tephra layers attributed to the Albano (Wulf et al., 2004) is rather different from that of the glass shards from Albano proximal deposits, determined for the first time only recently (Freda et al., 2006; Giaccio et al., 2007; De Benedetti et al., 2008). Furthermore, several Monticchio layers attributed to the Albano activity contain plagioclase crystals which, on the contrary, are virtually absent in the Albano pyroclasts (e.g. Freda et al., 2006).

### 3.2. $^{40}Ar/^{39}Ar$ geochronology

A comprehensive $^{40}Ar/^{39}Ar$ chronological framework for the eruptive history of the Albano maar has been recently provided by Freda et al. (2006) who dated six of the seven Albano units cropping out along the most complete stratigraphic section inside the crater as well as in other lesser mid-proximal sections. In particular, Freda et al. (2006) obtained two ages for the unit A1, one for A3, one for A4, two for A5, four for A6, and two for A7 (one of these latter was previously unpublished).

The results of this study allowed Freda et al. (2006) to divide the Albano maar history into two main, geochronologically distinct eruptive cycles, at 69 ± 1 ka and at 39 ± 1 through 36 ± 1 ka, comprising the groups of units A1–A2–A3 and A4–A5 and A6–A7, respectively. Details on the age of the single eruptive units are provided in Table 2.

**Table 2**
Results of the $^{40}Ar/^{39}Ar$ dating of the sampled Albano proximal and distal units (DUn) and Colle Iano accretionary lapilli-rich ash layer compared with the $^{40}Ar/^{39}Ar$ ages reported in Freda et al. (2006).

| Setting | Unit | Site | Age (ka ± 1σ) This study | Age (ka ± 1σ) Freda et al. 2006 | MSWD | Cryst n. | Sample | Locality |
|---|---|---|---|---|---|---|---|---|
| Distal | DU4 | 1 | 37.0±3.0 | | 1.1 | 7/7 | CSC1-DU4 | Casello San Cesareo |
| | DU3 | 1 | 41.0±7.0 | | 0.7 | 8/8 | CSC1-DU3 | Casello San Cesareo |
| | DU2 | 1 | 73.0±3.0 | | 1.1 | 8/8 | CSC-DU2 | Casello San Cesareo |
| | DU1 | 4 | 72.0±3.0 | | 0.5 | 7/7 | MF-DU1 | Monte Fiore |
| | Colle Iano | CI | 260±5 | | 0.8 | 8/8 | AH30-SF | Colle Iano |
| Proximal | A7 | 9 | 33.0±4.0 | | 0.5 | 4/4 | RP-A7 | Sporting R. di Papa |
| | | | | 36.0 ± 0.1* | 2.8 | 8/12 | AH18-C2 +GRA-C2bis | GRA |
| | | GA | | 36.1±0.2# | 1.5 | 6/6 | AH21-C3 | Galloro-b |
| | A6 | 9 | 36.0±3.0 | | 0.3 | 4/4 | RP-A6 | Sporting R. di Papa |
| | | 13 | 37.0±4.0 | | 2.0 | 7/11 | TAN-A6 | Tangenziale Albano 1 |
| | | 12 | 40.0±6.0 | | 1.0 | 6/8 | VDL-A6 | Crater rim |
| | | | | 36.1±0.3 | 1.5 | 12/20 | AH17-C3 | Valle delle Petrare |
| | | | | 35.7±1.1 | 1.8 | 8/8 | MAM-01 | Carcere Mamertino |
| | | | | 35.9±0.6 | 0.3 | 4/6 | AH-4Fbis | Galloro-a |
| | | | | 40.9±0.8 | 0.9 | 5/6 | AH3-C14 | Crater rim |
| | A5 | 13 | 40.0±6.0 | | 0.7 | 7/8 | TAN-A5 | Tangenziale Albano 1 |
| | | | | 39.0±0.3 | 2.8 | 4/6 | AH18-C3 | GRA |
| | A4 | | | 41.2±1.1 | 1.4 | 3/8 | AH3-C12 | Crater rim |
| | A3 | | | 68.6±1.1 | 1.4 | 6/6 | AH3-C9 | Crater rim |
| | A1 | | | 69.4±0.6 | 1.3 | 5/5 | AH3-A | Crater rim |
| | | | | 68.9±0.2 | 2.0 | 4/5 | AH18-C1 | GRA |

*Combined age of two samples.
#Previously unreported.

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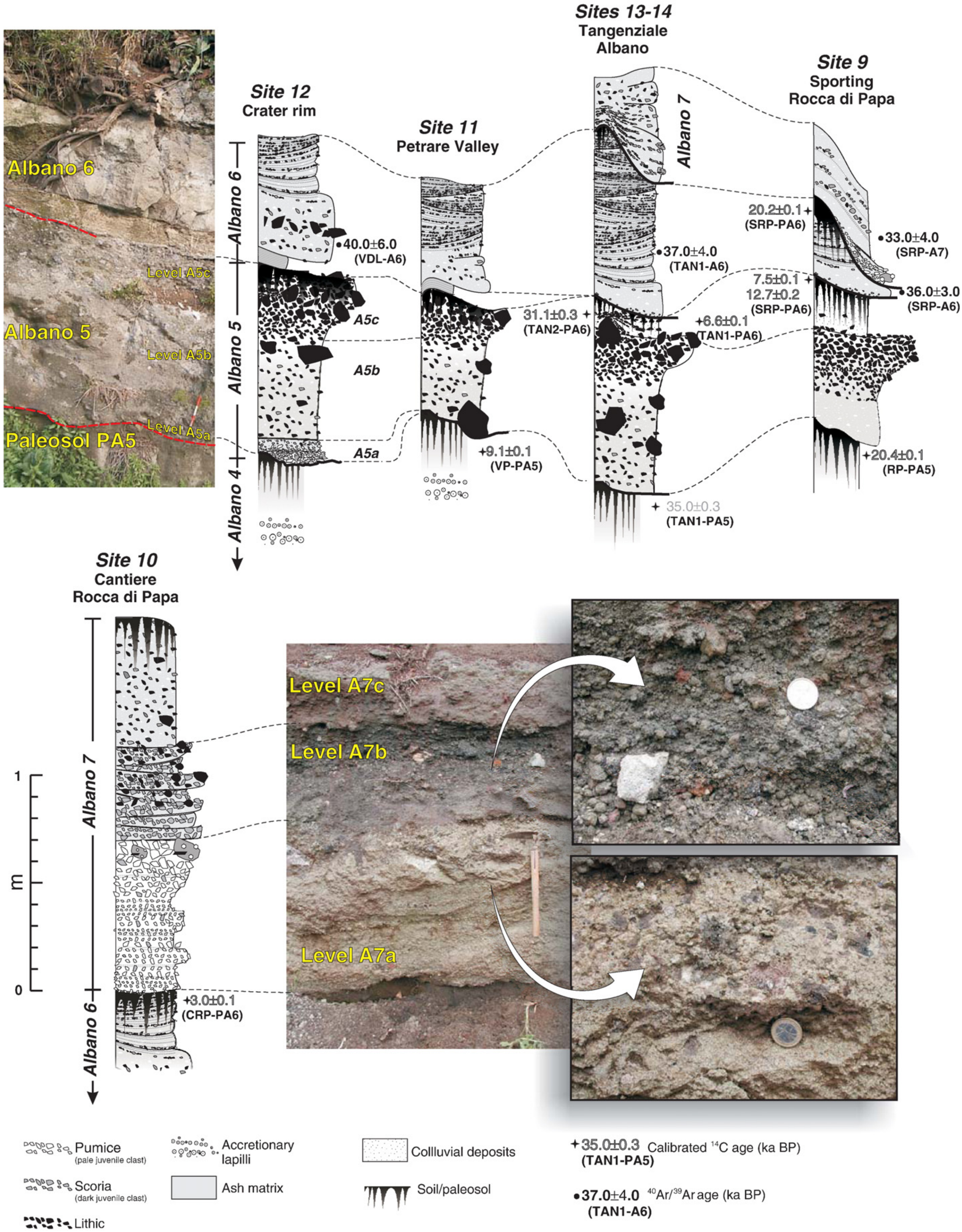


**Fig. 3.** Representative stratigraphic sections of the proximal density current deposits from Albano maar sampled for both $^{40}Ar/^{39}Ar$ and $^{14}C$ age determinations. Site locations in Fig. 1.

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### 3.3. Radiocarbon age determinations

The most reliable radiocarbon age determinations of products of the Albano maar were derived from two measurements performed on unburned wood fragments embedded within the "Peperino Albano", which yielded ages of 29,700 ± 400 (Fornaseri et al., 1963) and 29,858 ± 315 (Fornaseri and Cortesi, 1989) $^{14}C$ yr BP. According to the current available radiocarbon calibration datasets (e.g. Fairbanks et al., 2005), these two very concordant $^{14}C$ age determinations correspond at ca. 35 ± 1 cal ka, i.e. an age which overlaps that of 36 ± 1 ka obtained by $^{40}Ar/^{39}Ar$ method for the unit A6 or "Peperino Albano" (Karner et al., 2001, Freda et al., 2006).

Further two radiocarbon age determinations were performed by Funiciello et al. (2002) on the paleosol underlying the possibly reworked unit GRA4 (= A6; Table 1) cropping out to NW of the Albano maar (GRA and LR sections in Fig. 1). These samples of paleosol yielded ages of 5090 ± 100 and 5150 ± 70 $^{14}C$ years BP, respectively. These results led the Authors in considering the unit GRA4 and GRA5 (= A7) as products of lahar triggered by a catastrophic overspill of the Albano lake (Funiciello et al., 2002).

## 4. New geochronological data: sampling and dating procedure

We performed a total of 10 $^{40}Ar/^{39}Ar$ and 21 $^{14}C$ measurements on pyroclastc and paleosols samples, respectively, collected at 15 different sections representative of the three main stratigraphic domains described above (Fig. 1).

*$^{40}Ar/^{39}Ar$* – All the ten $^{40}Ar/^{39}Ar$ age determinations were performed on leucite crystals extracted from the juvenile clasts or from the ash matrix. Four samples derive from the sequence of the distal fallout units (Albano DU1, DU2, DU3 and DU4; Fig. 2) collected at two different sites; Casello S. Cesareo 1 (site 1, Fig. 1) (DU2, DU3 and DU4) and Monte Fiore (site 4, Fig. 1) (DU1), where the collected unit DU1 is intercalated in the lacustrine sequence containing also the unit DU2(= A3) and the distal equivalent of the unit A2 (Fig. 2). Five dated samples were collected from unit A7 (sample RP-A7), A6 (RP-A6, TAN-A6, VDL-A6) and A5 (TAN-A5) cropping out in the proximal area (Fig. 3; Table 2).

In addition, we also measured a sample (AH30-SF) collected from an accretionary lapilli-rich ash layer occurring at the base of a Strombolian scoria-fall deposits of the scoria cone of Colle Iano (site CI in Fig. 1) and attributed by Giordano et al. (2006) to the Campi di Annibale hydromagmatic activity and equivalent, according to the Authors, to the DUn of Giaccio et al. (2007).

For the $^{40}Ar/^{39}Ar$ analyses we used facilities and procedures similar to those described by Karner and Renne (1998). Neutron fluence monitors (standards) used for these experiments were Fish Canyon Tuff sanidine (28.02 Ma, Renne et al., 1998) or Alder Creek lava sanidine (1.194 Ma, Renne et al., 1998). Typically, six or more single-crystal total fusion analyses were performed on each sample. Only in a very limited number of cases the crystals were too small to yield sufficient Ar gas. In those cases we used two or possible three crystals in each laser disk. Ages are calculated from the error-weighted mean $^{40}Ar/^{39}Ar$ ratios (Renne et al., 1996). The best age estimate for each sample is the error-weighted mean age from the youngest statistically-consistent population of crystals, whereby the individual measurements were required to be within 2σ of the error-weighted mean value for inclusion in the best age calculation. This criterion was used to identify and eliminate xenocrysts or alteration from the best age estimate. Ages are reported with 1σ analytical precision in Table 2 and in the text; full analytical data are available as online supplementary material (Appendix A).

*Radiocarbon* – In spite of the considerable number of examined sections (Fig. 1), no alternative, better materials suitable for radiocarbon dating (e.g. charcoal fragments, unburned wood, etc.) than paleosols has been found. The samples were systematically collected from the uppermost horizons of the paleosols, immediately below the base of the volcanic units to be dated, unquestionably recognized as primary pyroclastic density current or fallout deposits. In order to minimize the effect of possible contaminations, deriving from percolation of younger organic material from higher horizons, we selected the sections with paleosols buried by at least 1.5–2 m of sediments.

Most of the 21 $^{14}C$ measurements were performed on the paleosols underlying the units occurring in the *distal fallout* area, where the pedogenized horizons appear substantially deeper and richer in organic matter than the remaining two subzones. In this area, we obtained 7 $^{14}C$ age determinations for the paleosol overlaid by the unit DU4, two for the paleosol overlaid by the unit DU3 and two for the paleosol underlying the unit DU2 (Fig. 2; Table 3).

Eight radiocarbon age determinations were performed on paleosols associated to the Albano deposits in the proximal area, however

**Table 3**
Results of the twenty-one radiocarbon age determinations of the paleosols associated to the Albano proximal or distal equivalent units (the label PAn/PDUn refers to the paleosol beneath unit An/DUn).

| Setting | Soil | Site | $^{14}C$ age | 2σ | Cal. age | 2σ | Sample | Laboratory | Locality |
|---|---|---|---|---|---|---|---|---|---|
| Distal | PDU4 | 1 | 23,460 | 140 | **28,100**[#] | 200 | CSC1-PDU4 | Beta analytic | Casello S. Cesareo |
| | | 1 | 27,020 | 400 | **32,300**[#] | 500 | CSC2-PDU4 | ETH | Casello S. Cesareo |
| | | 3 | 9690 | 50 | **11,100*** | 100 | SCCS-PDU4 | ETH | S. Ces, Campo Sport. |
| | | 5 | 17,910 | 115 | **21,200*** | 200 | LAR-PDU4 | ETH | Lariano |
| | | 6 | 11,090 | 85 | **12,900*** | 100 | VIV-PDU4 | ETH | Vivaro |
| | | 7 | 19,230 | 130 | **22,800*** | 200 | CI-PDU4 | ETH | Colle Iano |
| | | 8 | 19,780 | 145 | **23,600**[#] | 200 | CA-PDU4 | ETH | Campi di Annibale |
| | PDU3 | 1 | 23,760 | 190 | **28,500**[#] | 300 | CSC1-PDU3 | Beta Analytic | Casello S. Cesareo |
| | | 2 | 23,060 | 190 | **27,700**[#] | 300 | CSC2-PDU3a | ETH | Casello S. Cesareo |
| | PDU2 | 1 | 17,100 | 80 | **20,300*** | 200 | CSC1-PDU2 | Beta Analytic | Cas. S. Cesareo |
| | | 2 | 23,280 | 170 | **27,900**[#] | 200 | CSC2-PDU2 | ETH | Cas. S. Cesareo |
| Proximal | PA7 | 9 | 17,020 | 120 | **20,200*** | 100 | SRP-PA7 | ETH | Sporting Rocca di Papa |
| | | 10 | 2890 | 40 | **3000*** | 100 | CRP-A7 | Beta Analytic | Cantiere Rocca di Papa |
| | | 15 | 15,080 | 90 | **18,300*** | 200 | BC-PA7 | ETH | Bowling Ciampino |
| | PA6 | 9 | 6565 | 60 | **7500*** | 50 | SRP-PA5 | ETH | Sporting Rocca di Papa |
| | | *9* | *10,740* | *165* | ***12,700**** | *200* | SRP-PA5bis | ETH | Sporting Rocca di Papa |
| | | 13 | 5770 | 40 | **6600*** | 60 | TAN1-PA6 | Beta Analytic | Tangenziale Albano 1 |
| | | 14 | 25,890 | 240 | **31,100**[#] | 300 | TAN2-PA6 | ETH | Tangenziale Albano 2 |
| | PA5 | 9 | 17,230 | 110 | **20,400*** | 100 | SRP-PA5 | ETH | Sporting Rocca di Papa |
| | | 11 | 8130 | 55 | **9100*** | 70 | VP-PA5 | ETH | Valle Petrare |
| | | 13 | 29,570 | 270 | **35,000**[#] | 300 | TAN1-PA5 | Beta Analytic | Tangenziale Albano 1 |

Q1

*Calendar ages (ka BP) according to IntCal-04 radiocarbon calibration (Reimer et al., 2004).
[#]Estimated calendar ages (ka BP) according to Fairbanks et al. (2005).

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only a single measurement was obtained for a sample of paleosol collected in the area of the distal channeled deposits. Details on the dated units and section locations are provided in Table 3.

A preliminary set of six samples of paleosol was dated at the Beta Analytics Laboratory, Florida, either with the AMS technique (samples CSC1-PDU4, CRP-PA7, TAN1-PA6, CSC1-PDU3 and CSC1-PDU2) or with a standard radiometric technique (TAN1-PA5). The remaining 15 samples were analyzed at the AMS $^{14}C$ dating Lab of the ETH in Zurich. A first set of 9 samples (CSC2-PDU4, CSC2-PDU3, CSC2-PDU2, SRP-PA7, SRP-PA6, SRP-PA5, TAN2-PA6, LAR-PDU4, CA-PDU4) was stored at room temperature for several weeks. In order to avoid any possible post-sampling contamination, the last 5 samples (VIV-PDU4, CI-PDU4, SCCS-PDU4, VP-PA5, CB-PA7) were frozen immediately after sampling.

Samples have been wet sieved through a 250 µm sieve to remove possible contamination with rootlets. The standard procedure applied involved: 24 h treatment with 0.5 M HCl, at 60 °C, followed by rinsing to pH7, 6 h treatment with 0.1 M NaOH, at 60 °C, followed by rinsing to pH7, 6 h treatment with 0.4 M $H_2SO_4$ followed by rinsing to pH 7. Clean dry samples have been combusted in pre-cooked sealed quartz tubes. The low carbon content (on the order of 1% or less) required multiple combustion tubes for collection of 1 to 2 mg of C. The graphitization procedure applied in the AMS laboratory at ETH Zurich has been described by Hajdas et al. (2004). Radiocarbon ages are corrected for delta $^{13}C$ values.

## 5. Results and discussions

*$^{40}Ar/^{39}Ar$* — The results of the nine $^{40}Ar/^{39}Ar$ dating performed on the Albano distal or proximal units (Table 2) substantially replicate the chronological outline reported by Freda et al. (2006). Although the uncertainties of our new age determinations are considerably wider than previously obtained (due to the average smaller size of dated crystals and, possibly, larger extent of alteration and impurity), no appreciable age discrepancies between the two groups of data set are observed (Fig. 4).

Two samples from the unit DU1 and DU2 both collected in the area of the distal fallout deposits – Monte Fiore (sample VIV-DU1) and Casello S. Cesareo 1 (CSC1-DU2) – provided ages of 72 ± 3 and 73 ± 3 ka, respectively. These ages determinations are statistically indistinguishable from the $^{40}Ar/^{39}Ar$ age determinations obtained for the unit A1 and A3 reported by Freda et al. (2006), and thus confirm the correlation proposed by Giaccio et al. (2007).

No new age determination was performed on the unit Albano 4 dated by Freda et al. (2006) at 41 ± 1 ka (Table 2).

At sites 13 (Tangenziale Albano) and 1 (Casello S. Cesareo) (Figs. 1–3) two $^{40}Ar/^{39}Ar$ measurements performed on samples of the unit A5 and DU3 yielded ages of 40 ± 6 and 41 ± 7 ka, respectively, which confirm their previously proposed stratigraphic equivalence (Giaccio et al., 2007). These are the first two age determinations obtained for the unit A5 cropping out in both a proximal setting and the distal fallout area, respectively; previously it was dated only at GRA and LR sites in the area of the distal channeled deposits (Fig. 1) which yielded ages of 38.8 ± 0.2 and 39 ± 0.3. Standard deviation aside, again there is no substantial difference between the two set of dates.

Finally, we obtained three radiometric ages for the units A6, one for the units A7 and one for the unit DU4. The three samples of the unit A6, all from deposits cropping out in proximal area, yielded ages of 40 ± 6 (sample VDA-A6), 36 ± 3 (SRP-A6) and 37 ± 4 ka (TAN1-A6). The samples from unit DU4 and A7 collected at Casello S. Cesareo (site 1, Fig. 1) and at Sporting Rocca di Papa (site 9), nearest the crater rim, provided ages of 37 ± 3 and 33 ± 4, respectively. The age obtained for the unit DU4 replicates those reported by Freda et al. (2006) and in this study for the unit A7 (Table 2), confirming again their stratigraphic equivalence (Table 1).

Considering the previous radiometric ages reported by Freda et al. (2006), there is now a total of seven $^{40}Ar/^{39}Ar$ determinations for the unit A6 or Peperino Albano. Five of the seven age determinations available for the unit A6 cluster around 36 ka, whereas the remaining two would indicate an older age of about 40 ka. This inconsistency could be attributable to a possible occurrence of older contaminating xenocrysts of leucite, possibly deriving from the reworking of the unit A5 during the explosive event of the subsequent unit A6. On the contrary the four age determinations now available for the unit A7 or DU4 (Table 2) are consistent with an age of about 36 ka.

Finally, the sample (AH30-SF) collected from the accretionary lapilli-rich ash layer at the base of the scoria cone of Colle Iano yielded an age of 260 ± 5 ka, which rules out its equivalence to one of the DUn of Giaccio et al. (2007), here dated between ca. 72 and 36 ka, and definitively correlated to the Albano maar activity.



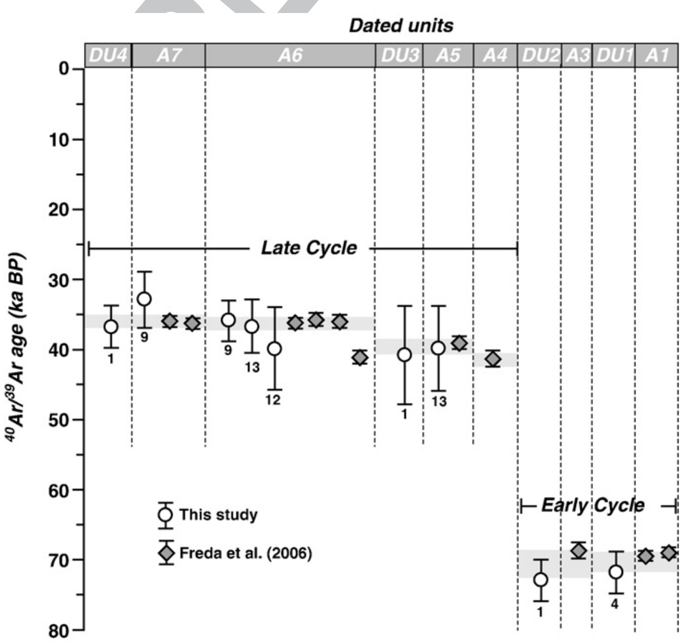


**Fig. 4.** Comparison between the $^{40}Ar/^{39}Ar$ age determinations obtained for the Albano proximal units (this study and Freda et al., 2006), and distal fallout (DUn of Giaccio et al., 2007). A considerable agreement between the two data-set, corroborating the proposed stratigraphic correlation (Table 1), may be observed. Numbers refer to the sampled sites (Fig. 1).

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In conclusion, in agreement with Freda et al. (2006) and Giaccio et al. (2007), our data confirm that the eruptive history of the Albano began ca. 70 ka with three explosive events related to the unit Albano 1, 2 and 3, two of which (A1 and A3, or DU1 and DU2) were deposited as fallout at greater distances eastward from the vent. These first three events occurred in a relative short time interval, not resoluble by the $^{40}Ar/^{39}Ar$ dating method. However, the stratigraphic clues from the lacustrine sequence of Monte Fiore would indicate that the time interval separating the unit A1 from the unit A2 was possibly different from that which occurred between the unit A2 and A3. At this site, in fact, more than three meters of lacustrine sediments separate the unit A1 from the couple of the unit A2 and A3 that are in strict stratigraphic proximity (Fig. 2). Therefore, by supposing for the lacustrine sediments a rather constant depositional rate, a substantial longer time interval separating the unit A1 from the unit A2, with respect to the A2-A1 inter-eruptive temporal-gap, may be supposed.

Jointly, our and Freda et al.'s (2006) data indicate that after these first three eruptions the Albano maar experienced a long phase of inactivity ending 30 ka later with the beginning of the late explosive cycles dated between 41 and 36 ka, which formed the suite of the units A4, A5, A6 and A7. In agreement with the pedostratigraphic evidence summarized in Section 2, the $^{40}Ar/^{39}Ar$ dating suggest a very short temporal recurrence between the eruptions related to the units A6 and A7, not resolvable through $^{40}Ar/^{39}Ar$ measurements. Concurrently with Giaccio et al. (2007), our results also confirm that during this second cycle of activity the fifth and seventh explosive events were substantially larger than the fourth and sixth, and the related units A5 (=DU3) and A7(=DU4) were deposited as fallout and/or surge layers on a much wider area.

*Radiocarbon* – In contrast with the general agreement and stratigraphic concordance of the $^{40}Ar/^{39}Ar$ geochronology, the results of the 21 radiocarbon measurements strongly conflict with both the stratigraphy and $^{40}Ar/^{39}Ar$ chronological framework (Table 3, Fig. 5).

Ten radiocarbon measurements performed on the paleosols underlying the unit A7, or the equivalent DU4, dated at ca. 36 ka according to $^{40}Ar/^{39}Ar$ chronology, yielded extremely scattered ages between 32 and 3 cal ka (Table 3, Fig. 5). As most inconsistent appear the results of the remaining eleven radiocarbon datings performed on the units A3, corresponding to the unit DU2, A5, correlated to the unit DU3, and A6. Even for the unit A3/DU2 (ca. 70 ka), expected to be well beyond the limit of the $^{14}C$ method, the results of two radiocarbon measurements yielded the surprising young ages of c. 28 and 18.5 cal ka (Figs. 2 and 5). As a whole, the $^{14}C$ measurements provide ages systematically younger than the $^{40}Ar/^{39}Ar$ ones and largely inconsistent among them. Just in a couple of cases the results of the radiocarbon determinations of the unit A5, A6 and A7, or equivalent distal units, yielded age of 35, 31 and 32 cal ka (samples TAN1-PA5, TAN2-PA6, CSC2-PDU4, respectively) approximating the ages determined by the $^{40}Ar/^{39}Ar$ method (Fig. 5); even so, however, the former are still at least some thousands of years younger.

Considering the significant consistence of the $^{40}Ar/^{39}Ar$ chronological framework, the scattered and contradictory results of the $^{14}C$ dating indicate that the paleosols were to variable extents affected by contaminations by younger organic carbon.

Indeed, the accurate dating of soil carbon is notoriously complex (Madsen et al., 1998) due to a large variety of potential contamination vectors (Evans, 1985; Scharpenseel, 1971; Scharpenseel and Schiffmann, 1977; Chichagova and Cherkinsky, 1993). A vast literature describes the problems related to radiocarbon dating of paleosols, making "soil age" definable and applicable for absolute dating in limited cases, only for well-sealed paleosols, charcoal or wood relics (Scharpenseel and Becker-Heidmann, 1992, Becker-Heidmann and Harkness, 1995). The case of shallow soils is particularly problematic since they often remain in an open system causing a significant underestimation of the true age (Orlova and Panychev, 1993). This may be indeed the case of our dated horizons, which manifestly were not completely sealed by the overlaying pyroclastic deposits, often represented by loose, highly permeable and not really thick (1–2 m) sediments.

Accidental contaminations during the sampling or storing of the samples should be ruled out because even the second set of samples dated at the ETH laboratory, which after the sampling was immediately frozen, provided the same inconsistent and too young ages.

Noteworthy, the best $^{14}C$ ages approximating the $^{40}Ar/^{39}Ar$ dating were obtained from the deeper and/or well sealed paleosols, as it is for instance the case of the paleosol below the thick and well lithified unit A5 at the Tangenziale site, which yielded a calibrated radiocarbon

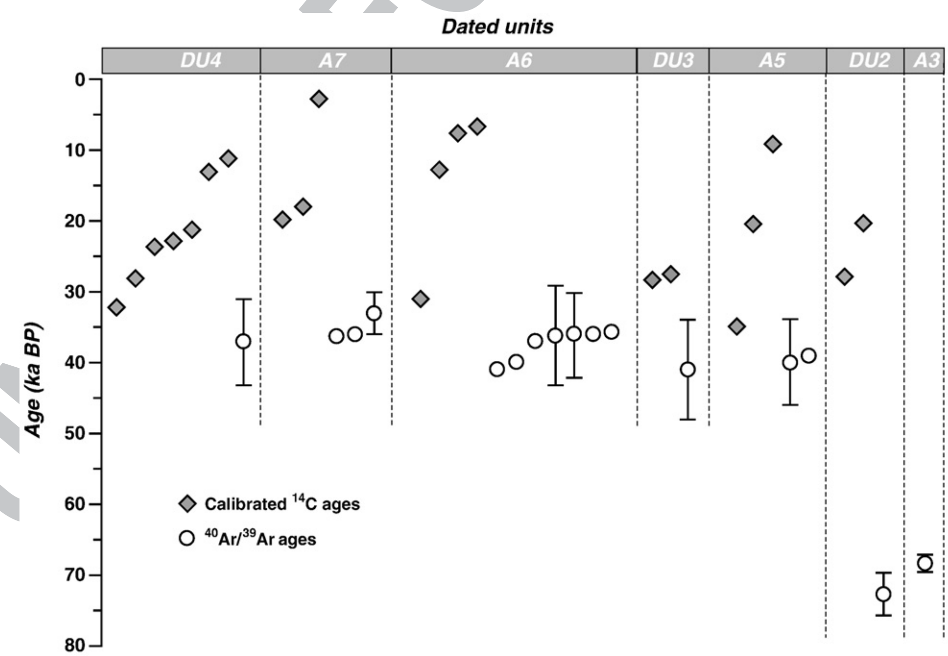


**Fig. 5.** Comparison between the $^{40}Ar/^{39}Ar$ dating available for the unit Albano 3, 5, 6 and 7, or distal equivalents, (Table 2) and the $^{14}C$ age determinations of the associated paleosols sampled in all the depositional setting of the (*i*) pyroclastic density current, (*ii*) channeled and (*iii*) fallout deposits. Note the substantial stratigraphic inconsistencies and highly scattering of the $^{14}C$ ages.

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age of about 35 ka. It is just as important to underscore that the two available radiocarbon age determinations, performed on unburned wood fragments embedded in the *Lapis Albanus*, are statistically indistinguishable from the $^{40}Ar/^{39}Ar$ ages (Table 2).

In conclusion, we are inclined to claim that the extent of the contamination processes, driven by a series of local unfavorable stratigraphic conditions – such as faintly developed paleosols; shallow burial; presence of highly permeable sediments – makes the radiocarbon measurements on paleosols unsuitable for dating the Albano maar eruptive units, and hence for assessing its activity status and potential connected hazard.

In the light of our results, the reliability radiocarbon age determinations performed on the paleosols associated to the Albano units at GRA site, evidencing a possible Holocene catastrophic activity of the volcano (e.g. Funiciello et al., 2002, 2003), should be accordingly re-evaluated. The GRA units can be in fact equally interpreted either as actual Holocene lahars or as more ordinary sin-eruptive volcaniclastic deposits, wholly equivalent to those recognized in the wide area of the Albano fallout deposits, within and beyond the rim of major Tuscolano-Artemisio caldera (Giaccio et al., 2007), i.e. in a geomorphological setting which firmly excludes any possible hydraulic connection with the Albano lake overspill (Fig. 1).

## 6. Conclusions

Nine $^{40}Ar/^{39}Ar$ and 21 $^{14}C$ measurements performed on five of the seven Albano maar pyroclastic products and related paleosols, describe resolutely the history of the most recent explosive activity at Colli Albani Volcanic District, providing decisive evidence to resolve some inconsistent geochronological data which recently led in reconsidering the activity status of the volcano.

The new set of $^{40}Ar/^{39}Ar$ age determinations reiterated to a large extent the results obtained with the same method by Freda et al. (2006) strengthening their conclusion. Equally, according to both sets of $^{40}Ar/^{39}Ar$ ages, two main eruptive phases, separated by a 30 ka-long period of quiescence, can be recognized: (*i*) an Early phase centered around 70 ka, comprising the first three eruptive units Albano 1, 2 and 3 (A1, A2 and A3), and (*ii*) a Late phase dated between 41 and 36 ka, during which occurred the four last eruptions of the units A4, A5, A6 and A7.

This eruptive history was outlined by dating virtually all the Albano units (A1, A3, A4, A5 A6 and A7) occurring in the three main recognized stratigraphic settings; i.e. the pyroclastic density current deposits at near vent sections, the distal fallout units, outcropping as far as 15 km northeast from the vent, and channeled lithofacies of the Ciampino Plain, in the area of the south-eastern suburbs of Rome.

As previously reported in Giaccio et al. (2007), our results also confirm that during these two cycles of activity the intensity and eruptive style were not uniform, and four of the seven explosive events were characterized by the formation of sub-Plinian convective columns which led the deposition of the units A1, A3, A5 and A7 as fallout deposits at considerably greater distances from the vent than those reached by the units A2, A4 and A6. The attribution of these sub-Plinian fallout deposits to the Campi di Annibale hydromagmatic center (Giordano et al., 2006) should therefore be reconsidered.

In contrast with the $^{40}Ar/^{39}Ar$ age determinations, the twenty-one radiocarbon measurements yielded stratigraphically inconsistent and highly scattered ages, systematically younger than the $^{40}Ar/^{39}Ar$ dating. In some cases the extent of the contamination was so high as to shift the ages of the unit A7, A6 and A5, dated between 40 and 36 ka, to the Holocene period.

For the present study, we interpret the concordant $^{40}Ar/^{39}Ar$ age data to be more reliable than the $^{14}C$ data, and we regard the latter resulting from a variable but often sizeable contamination with younger organic carbon that altered the original $^{14}C$ concentration in the buried soils, which have remained in an open system.

In light of these result, and awareness of the potential, very high contamination of the soils buried by the Albano deposits, we are drawn to conclude that the age of the recent volcanic activity, or other dangerous phenomena, that occurred at Colli Albani Volcanic District cannot be assessed exclusively on the basis of the $^{14}C$ chronology on paleosols. Actually, in the absence of additional, really reliable stratigraphic-chronological evidence, the radiocarbon age determinations on paleosols can themselves dramatically underestimate the age of some catastrophic events, misleading the assessment of the current activity status of the Colli Albani Volcanic District.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jvolgeores.2009.05.011.

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